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# Frequency-doubled DBR-tapered diode laser for direct pumping of Ti:sapphire lasers generating sub-20 fs pulses

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**Abstract:** For the first time a single-pass frequency doubled DBR-tapered diode laser suitable for pumping Ti:sapphire lasers generating ultrashort pulses is demonstrated. The maximum output powers achieved when pumping the Ti:sapphire laser are 110 mW (CW) and 82 mW (mode-locked) respectively at 1.2 W of pump power. This corresponds to a reduction in optical conversion efficiencies to 75% of the values achieved with a commercial diode pumped solid-state laser. However, the superior electro-optical efficiency of the diode laser improves the overall efficiency of the Ti:sapphire laser by a factor  $> 2$ . The optical spectrum emitted by the Ti:sapphire laser when pumped with our diode laser shows a spectral width of 112 nm (FWHM). Based on autocorrelation measurements, pulse widths of less than 20 fs can therefore be expected.

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**OCIS codes:** (140.2020) Diode lasers; (140.5560) Pumping; (140.3590) Lasers, titanium; (140.7090) Ultrafast lasers.

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## 1. Introduction

Within the group of solid state lasers, Ti:sapphire lasers ( $\text{Ti}:\text{Al}_2\text{O}_3$ ) are one example using transition-metal-ion-doped laser crystals [1]. Lasers based on such crystals are usually tunable over a wide spectral range. In the case of  $\text{Ti}^{3+}$ -doped  $\text{Al}_2\text{O}_3$  the laser emission can be tuned over 500 nm ranging between 600 nm to 1100 nm [1,2]. This of course makes Ti:sapphire lasers very attractive for several applications and they have been widely used within imaging [3–5], spectroscopy [6–8] or materials processing [9–11]. Due to the broad tunability Ti:sapphire lasers are capable of generating ultrashort fs laser pulses [12].

Because the  $\text{Ti}:\text{Al}_2\text{O}_3$  crystals absorb most efficiently at wavelengths around 500 nm [1,13], argon-ion lasers as well as frequency doubled Nd:YAG and Nd:YLF lasers, thin disk lasers and fiber lasers have been used as pump sources [13–17]. These lasers are capable of emitting multiple watts of output power in the blue-green spectral range, but typically increase the dimensions and costs of Ti:sapphire laser systems. As an alternative, diode lasers are also

capable of emitting several watts but with high electro-optical conversion efficiencies reaching up to 73% [18,19]. Their reduced dimensions allow for compact and cost effective systems. Furthermore, their material compositions result in a certain wavelength flexibility compared to lasers based on atomic transitions [20], which might provide advantages for the optical pumping. Using this principle Resan et al. demonstrated a frequency doubled optically pumped semiconductor laser emitting 5 W of output power at 532 nm [21]. When pumping a Ti:sapphire gain medium, they achieved an average output power of 0.5 W and generated 12.6 fs pulses. In this concept, a diode laser bar is used to pump a vertical emitting semiconductor gain medium. The green light is then generated by intracavity frequency doubling, i.e. two frequency conversion processes are required. To ease this principle and avoid many light conversion stages that decrease the systems' efficiency one could either use direct emitting diode lasers or simply frequency doubled edge emitting diode lasers. This highly increases the potential of developing low-cost Ti:sapphire lasers with higher efficiencies and smaller footprints. Recently GaN based diode lasers emitting around 450 nm have been demonstrated to be capable of pumping Ti:sapphire lasers [22]. Here 114 fs pulses with an average power of 13 mW were demonstrated using 1 W of pump power. Unfortunately, pumping at this short wavelength introduced additional losses limiting the performance. In the green spectral range InGaN-based laser diodes are capable of emitting up to 50 mW already [23], but still far away from the green output powers mentioned above. Much higher outputs can be achieved by frequency doubling of high-power edge emitting diode lasers. In this context 1060 nm distributed Bragg reflector (DBR)-tapered diode lasers were demonstrated, emitting 12 W of output power with nearly diffraction limited beam qualities up to 10 W [24]. Single-pass frequency doubling of these lasers resulted in 1.58 W of green light [25]. This was the first time this power level has been reached, enabling competitive direct optical pumping.

In this paper we demonstrate, based on these results, a simple and robust light source suitable for pumping an ultrafast Ti:Al<sub>2</sub>O<sub>3</sub> laser. To classify our results, the single-pass frequency doubled diode laser is compared to a commercially available DPSS-laser system pumping the same oscillator. Using our light source, the Ti:sapphire laser emits maximum powers of 110 mW (CW) and 82 mW (mode-locked) at 1.2 W of pump power. Deviations up to 30 mW compared to the commercial pump laser are compensated by the much higher electro-optical efficiency of the diode laser. The optical spectrum of the mode-locked Ti:sapphire laser with an output power of 52 mW has a measured spectral width of 112 nm (FWHM). The corresponding autocorrelation signal indicates that pulse widths of less than 20 fs can be expected using our laser. To the best of our knowledge, this represents the first time a high-power single-pass frequency doubled tapered diode laser is used for pumping a mode-locked Ti:Al<sub>2</sub>O<sub>3</sub> laser to generate ultrashort laser pulses.

## 2. Experimental setup

The scheme of the frequency doubled diode laser is shown in Fig. 1. A detailed description of the structure and layout of the 1060 nm DBR-tapered diode lasers can be found in [24,26]. The 6 mm long laser is mounted p-side up on a CuW heat spreader, which itself is mounted on a 25 x 25 mm<sup>2</sup> conduction cooled package (CCP) mount allowing for efficient cooling. The laser consists of an unpumped 1 mm long 6th order surface grating [27] followed by a 1 mm ridge waveguide (RW) and a 4 mm long tapered section. The current to the ridge waveguide and the tapered section are controlled individually. The laser radiation is collimated in both axes using AR-coated lenses to avoid optical feedback. Collimating the fast axis is done by an aspheric lens with a focal length of 3.1 mm and a numerical aperture of 0.68. The slow axis is collimated by a cylindrical lens with a 15 mm focal length. This generates a nearly circular beam of about 2 mm in diameter and compensates for astigmatism, originating from the tapered diode laser.

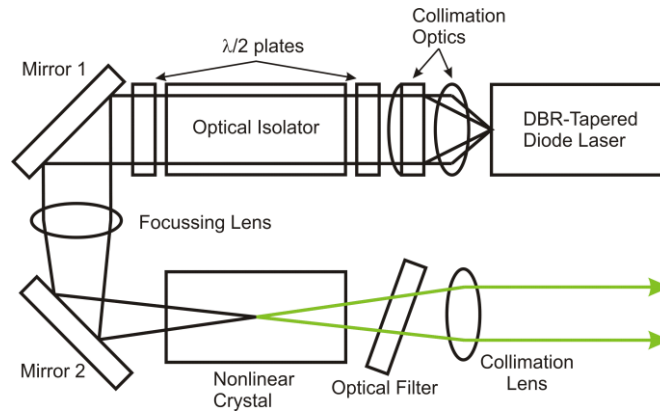


Fig. 1. Sketch of the frequency doubled diode laser system based on single-pass second harmonic generation.

To avoid any kind of optical feedback to the laser, two half-wave plates and a 30 dB optical isolator are placed in front of the laser. The half-wave plate closer to the laser is used to adjust the polarization as required by the isolator. The second half-wave plate then corrects the polarization as required for efficient SHG. Regulating the output power by changing the injection current of tapered diode lasers immediately affects the astigmatism and would require a re-positioning of the cylindrical lens. Instead, the first half-wave plate can be used. The power available for frequency doubling is then simply adjusted by rotating this half-wave plate without changing the current or re-positioning any lenses.

Regarding single-pass frequency doubling, a few changes are made compared to the setup published before [25]. After the emission passes the second half-wave plate, two folding mirrors are used to reduce the overall size of the setup. In between the mirrors a lens with a focal length of 100 mm generates a beam waist in the nonlinear crystal with a radius of approximately 60  $\mu\text{m}$ , which proved to be optimum in the experiments. The crystal is a plain cut, periodically poled, MgO-doped lithium niobate (PPMgLN) crystal (*HCPhotonics*), poled with a period of 6.92  $\mu\text{m}$ . Its dimensions are  $L \times W \times H = (30 \times 2 \times 0.5) \text{ mm}^3$ . Both facets are antireflection coated at 1064 nm and 532 nm. Behind the nonlinear crystal an optical filter is used to separate the frequency doubled beam from the fundamental beam. A collimation lens with a focal length of 200 mm then generates an approximately 2.5 mm wide circular green beam for pumping the Ti:sapphire laser.

The scheme of the Ti:sapphire laser cavity is shown in Fig. 2. A similar compact and low-cost oscillator is described in [28] showing high potential for clinical applications while offering user friendliness, high stability and reproducibility. In this oscillator, a spherical lens with a focal length of 35 mm is used to focus the green beam into a 3 mm long Ti:Al<sub>2</sub>O<sub>3</sub> crystal (figure of merit  $> 150$ , absorption coefficient  $\alpha = 4.5 \text{ cm}^{-1}$ ) positioned at Brewster angle inside a x-folded, Kerr lens mode-locked oscillator. The laser cavity consists of several chirped mirrors to compensate for dispersion and two curved mirrors ( $R = 50 \text{ mm}$ ), generating a beam waist of about 18  $\mu\text{m}$  inside the laser crystal. One curved mirror is also used to adjust the stability range of the cavity. On the other hand external perturbations to one of the end-mirrors are used to initiate mode-locking. The total length of the cavity is about 1.75 m resulting in a repetition rate of approximately 80 MHz. At each round-trip 3% of the generated laser emission is coupled out for measurements.

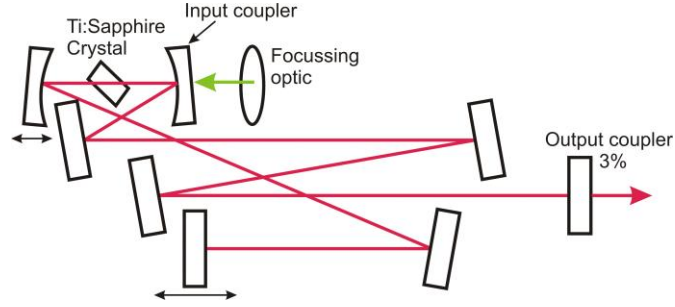


Fig. 2. Illustration of the x-folded, Kerr lens mode-locked Ti:sapphire oscillator with a cavity length of 1.75 m.

### 3. Characterization of the pump lasers

For the experiments, the injection current to the ridge waveguide section of the diode laser is set to 300 mA. The tapered section is operated at 14 A, resulting in a maximum available infrared power of 8.8 W. A more detailed characterization of a comparable laser including power current characteristics, spectral characteristics and wavelength dependence on temperature and current can be found in [25]. To achieve optimum phase matching in the nonlinear crystal the temperature of the laser is stabilized at 17.66 °C. The nonlinear crystal is temperature stabilized at 37 °C. Figure 3(a) shows the achieved green output power with respect to the fundamental infrared pump power. At the described settings a maximum green power of 1.28 W is achieved. This corresponds to a conversion efficiency of 14.5% from infrared to green light and to an electro-optical efficiency of about 4% respectively. The normalized conversion efficiency  $\eta_{norm}$  is calculated for second harmonic generation with pump depletion using the following relation [29].

$$P_{SHG} = P_{FUNDAMENTAL} \times \tanh^2 \left( \sqrt{\eta_{norm} \times P_{FUNDAMENTAL}} \right) \quad (1)$$

Here  $P_{FUNDAMENTAL}$  is the fundamental pump power, and  $P_{SHG}$  is the power of the second harmonic. The resulting fit shows good agreement with the measured data and gives a normalized conversion efficiency of approximately 1.9%/W.

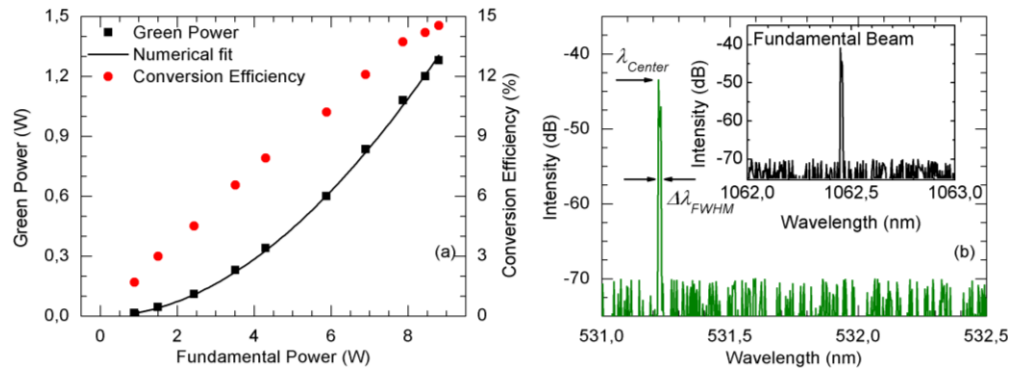


Fig. 3. (a) SHG output power and corresponding conversion efficiency versus fundamental pump power. The numerical fit is based on the depleted pump approximation valid for low power SHG. (b) Optical spectra of the second harmonic and the fundamental beam measured at maximum fundamental pump power.

The optical spectra at these settings are measured with an optical spectrum analyzer with a resolution limit of 6 pm in the near-infrared (*Advantest Q8347*). The emission wavelength of the fundamental beam is 1062.45 nm, shown by the inset in Fig. 3(b). The spectrum of the

second harmonic beam therefore shows a center wavelength of 531.22 nm. Due to the intrinsic wavelength stabilization the DBR-tapered diode laser emits light in a single longitudinal mode, resulting in a measured spectral width of 6 pm (FWHM) limited by the resolution of the spectrum analyzer. The side mode suppression is above 25 dB, limited by the dynamic range of the optical spectrum analyzer.

Additionally the beam propagation parameters of the frequency doubled beam are calculated by measuring the beam profiles along the beam waist of the focused beam with a beam scanner (Photon, Inc) and fitting the measured  $1/e^2$  beam widths to a least-squares hyperbolic equation (Fig. 4). At maximum green output power, the achieved  $M^2$  values are 1.3 in the fast axis and 1.4 in the slow axis. Considering the short length of the Ti:sapphire crystal it's especially the near field contributing to the pumping process. In this regard the insets in Fig. 4 show the corresponding beam profiles in the focus area. For both axes additional structures in the lower wings of the profiles compared to a Gaussian fit can be seen, possibly reducing the beam quality and affecting the efficiency of the direct pumping.

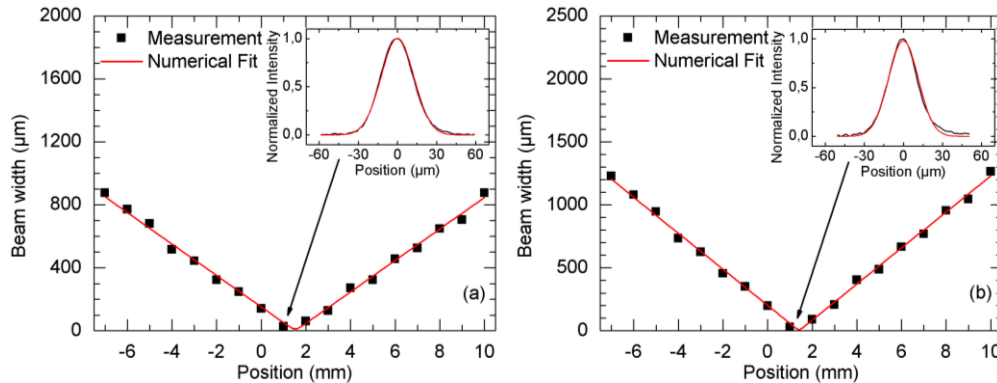


Fig. 4. Beam caustics and near field beam profiles of the generated green beam. (a) fast axis, (b) slow axis.

The laser system used for comparison is a commercially available diode pumped solid-state laser (*Laser Quantum, Excel Laser*), offering a maximum green power of 1.5 W at 532 nm. The electro-optical efficiency is below 2%. The output beam is near diffraction limited with beam propagation parameters measured to be  $M^2 < 1.1$  and a beam size of 1.8 mm.

#### 4. Experimental results of pumping a Ti:sapphire laser

The Ti:sapphire oscillator is built up based on the commercial diode pumped solid-state laser. At a pump power of 1.5 W the Ti:sapphire laser shows a maximum output power of 180 mW (Fig. 5(a)), resulting in a conversion efficiency of 12% from green to near-infrared.

When replacing the commercial laser with our laser system a maximum power of 105 mW is achieved at a pump power of 1.1 W. The corresponding conversion efficiency is 9.5%. To analyze the influence of the beam diameter on the conversion efficiency, the experiment is repeated, replacing the 200 mm collimation lens with a lens of 160 mm focal length. This reduces the beam diameter of our laser system to approximately 2 mm, close to the beam size of the commercial system. Despite changing the lenses the effect on the efficiency is more or less negligible. At a pump power of 1.2 W a maximum power of 110 mW is achieved, resulting in a conversion efficiency of 9.2%.

When comparing the results achieved at similar pump powers using different lasers, the output power of the Ti:sapphire laser differs by 20 to 30 mW in favor of the commercial pump laser. This corresponds to a drop in optical conversion efficiency to 75% of the values achieved with the commercial laser. However, the overall efficiency of the Ti:sapphire laser is improved by a factor  $> 2$ , due to the much higher electro-optical efficiency of the diode laser



module. A rough estimation of the pump threshold shows an increase from 0.2 W to 0.33 W when switching to the diode laser. The slope efficiency decreases from 13.8% to 12.7%.

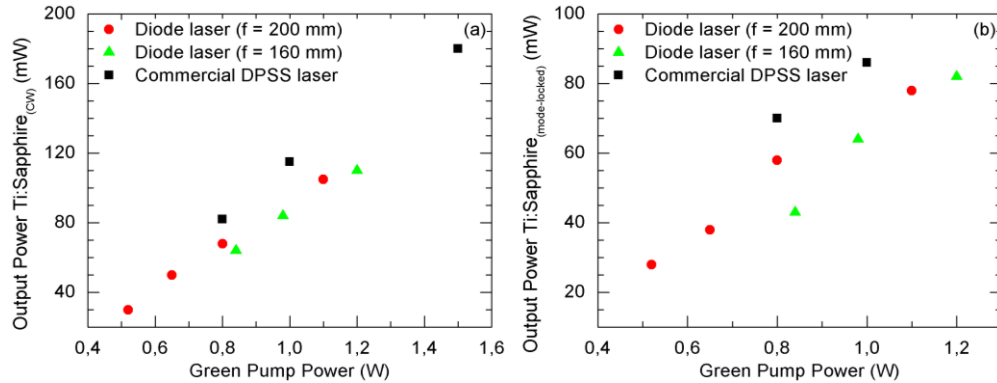


Fig. 5. (a) Comparison of CW power characteristics of the Ti:sapphire laser using different pump sources. For the experiments, two different lenses collimate the green beam of the diode laser system. (b) Comparison of mode-locked power characteristics of the Ti:sapphire laser.

The deviation in conversion efficiency also holds when mode-locking the Ti:sapphire laser (Fig. 5(b)). Here a maximum output power of 78 mW is achieved using the frequency doubled diode laser with a 200 mm collimation lens. The corresponding conversion efficiency at a pump power of 1.1 W is 7.1%. Again, changing the lens has very little effect on the efficiency. With a conversion efficiency of 6.8% a maximum power of 82 mW is achieved at a pump power of 1.2 W. The maximum power measured for the commercial laser at 1 W of pump power is 86 mW, resulting in a conversion efficiency of 8.6%.

The observed deviations between the two pump sources could be explained by slightly reduced beam qualities. When pumping a Ti:sapphire laser, beams with inferior beam qualities will have larger beam waists negatively affecting the overlap between the green and the generated near-infrared beam, reducing the overall conversion efficiency. A second explanation could be the oscillator being built based on the commercial laser. Optimizing the oscillator with respect to our laser could therefore help to decrease and even eliminate these differences. A third explanation could still be differences in beam sizes affecting the conversion efficiencies. A difference in polarizations between the two pump sources could also be a reason but can be neglected in case of optimum single-pass frequency conversion.

In order to estimate the width of pulses that could be generated using the frequency doubled diode laser as a pump source, interferometric autocorrelation traces are measured. For this experiment the green beam of our laser is collimated using the 160 mm collimation lens. Figure 6(a) shows the comparison between the measured spectra emitted by the mode-locked Ti:sapphire laser when using two different pump sources. In both cases the pump power is set to 1.2 W of green light resulting in 52 mW (diode laser) and 60 mW (commercial laser) respectively, emitted by the Ti:sapphire laser. The drop in output power compared to the data shown above can be explained by changes made to the oscillator to achieve minimum pulse widths. Using the diode laser based pump source the measured spectrum shows a spectral width of 112 nm (FWHM), resulting in a spectral band width of 54 THz. The full width ( $1/e^2$ ) is 178 nm. The spectral width using the commercial laser is 115 nm (FWHM). The side-peaks at 700 nm can be explained by a sharp phase change caused by the chirped mirrors.

After measuring the spectrum, the Ti:sapphire laser beam is sent into an optical autocorrelator. Figure 6(b) shows the normalized autocorrelation trace. Based on these measurements pulse widths of less than 20 fs can be estimated, matching the expectations for this oscillator. The bumps left and right of the autocorrelation trace can be explained by slightly imperfect dispersion management within the oscillator. As the spectrum is not



Gaussian like, the pulses are not transform limited. Nevertheless, the results clearly indicate the potential of the proposed pump scheme.

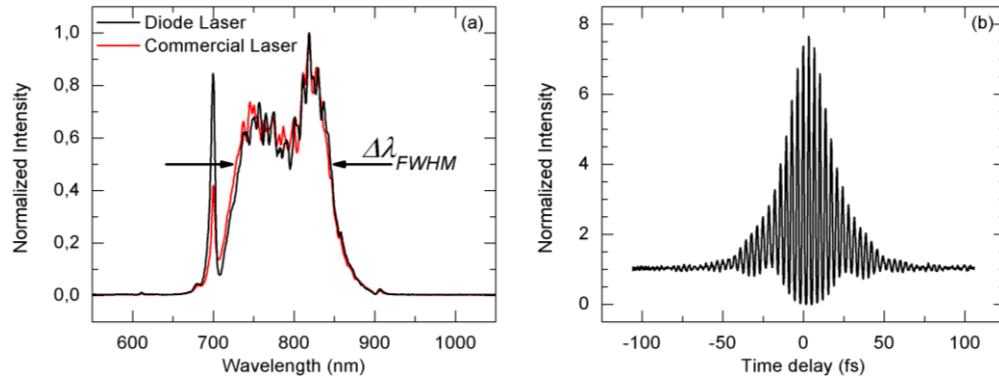


Fig. 6. (a) Optical spectrum of the mode-locked Ti:sapphire laser directly pumped by a frequency doubled diode laser (black line) and a commercial DPSS laser (red line). (b) Autocorrelation signal of the mode-locked Ti:sapphire laser directly pumped by the frequency doubled diode laser.

## 5. Conclusion

For the first time a single-pass frequency doubled tapered diode laser based system is demonstrated as an alternative pump source for pumping mode-locked Ti:sapphire lasers generating ultrashort laser pulses. The maximum output power achieved when using our pump laser is 110 mW (CW) and 82 mW (mode-locked) respectively. Deviations of up to 30 mW compared to an established, commercial DPSS laser system can be explained by slightly reduced beam qualities, the adaption of the oscillator being built with regard to the commercial pump source and deviations in beam sizes. The optical spectrum emitted by the Ti:sapphire laser at 52 mW shows a spectral width of about 112 nm (FWHM). From the corresponding autocorrelation signal, pulse widths of less than 20 fs can be expected.

These results indicate that in the future a simple and robust diode laser based pump source could be an alternative for pumping Ti:sapphire lasers. The superior electro-optical efficiency as well as the reduced dimensions of diode lasers could help to increase the overall efficiency of Ti:sapphire laser systems while reducing their costs and overall footprints. Last but not least, improvements in diode laser technologies leading to longer tapered lasers with higher output power might help to push the performance of green diode laser modules towards the 3-4 W range.